[2.2]Paracyclophane-based coumarins: effective organo-photocatalysts for light-induced desulfonylation processes

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Abstract: *Herein, we demonstrate for the first time that coumarins derived from [2.2]paracyclophane (pCp) can act as effective organo-photocatalysts and promote the reductive cleavage of sulfonamides under light-irradiation. In the presence of these original compounds, photodesulfonylation reactions occur under mild conditions at low catalyst loadings in the presence of Hantzsch ester. Theoretical and experimental investigations are described, which elucidate the reaction mechanism and the nature of the active species involved in the photocatalytic process. This proof-of-concept study paves the way for further application of pCps in the field of photocatalysis.*

[2.2]Paracyclophane (pCp) is an original organic molecule that possesses a unique three-dimensional structure. Described for the first time by Brown and Farthing in 1949,[1] this compound incorporates two benzene rings stacked in a face-to-face geometry and linked together by two ethylene bridges at their *para* position.[2] pCp displays unusual optoelectronic properties due to the proximity of its aromatic cores that favours through-space and through-bond interactions.[3] As a result, this substrate and its derivatives have been extensively used in material science as building-blocks for the development of various luminescent objects.[4] These compounds have also frequently served as precursors to obtain aromatic polymers or functionalized surfaces using chemical vapor deposition (CVD) methods.[5] In addition, substituted pCps can show planar chirality[6] and have been increasingly employed over the years as ligands or catalysts in stereoselective synthesis[7] or as scaffolds for the development of chiroptical dyes.[8]

Despite their interesting photophysical and catalytic behaviours that have led to such a wide range of applications, [2.2]paracyclophanes have rarely been considered as useful precursors for the development of novel photocatalysts. This possibility was nonetheless anticipated by Hopf as early as 1991.[9] Recently, an example of a heterobimetallic photoredox complex based

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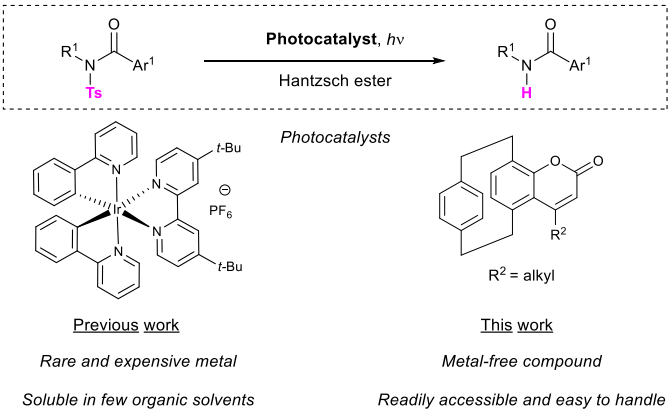
on a pCp backbone has been reported by Bräse and co-workers.[10] However, to the best of our knowledge, no examples of organo-photocatalysts derived from [2.2]paracyclophanes have been described to date.

Herein, we demonstrate for the first time that pCp-fused coumarin systems can play the role of photoredox catalysts and promote the reductive cleavage of sulfonamides under light-irradiation.

Sulfonamides display several advantageous properties including general inertia to acids, bases, or electrophiles and stability under oxidizing or mild reducing conditions. The difficult cleavage of these compounds, however, still greatly limits the use of such functions as amine protecting groups in organic synthesis. Indeed, removal of *N*-sulfonyl moieties usually involve treatments with strong reducing agents, acids or bases.[11] Electrochemical methods or procedures relaying on SmI_2-promoted electron transfer reactions have also been described in the literature.[12] Recently, photocatalytic processes have unlocked new possibilities for performing light-driven desulfonylation reactions under milder conditions, and few examples have been reported. These include, for instance, the use of extremely potent acridine radical photoreductants.[13] Methods involving different organophotocatalysts in the presence of hydride donors[14] or expensive transition metal complexes in combination with Hantzsch esters (HE) have also been developed.[15]

Coumarin dyes are known to be able to mimic powerful reductant [Ir(III)] complexes in various light-promoted transformations, such as the radical coupling of carbonyl compounds and imines, the trifluoromethylation of alkenes or the reductive protonation of bromoketones. [16]



Scheme 1. Examples of catalytic photodesulfonylation reactions

On the basis of our ongoing work on the synthesis and spectroscopic characterization of small three-dimensional dyes derived from [2.2]paracyclophane,[17] we envisaged the possibility to employ luminescent pCp-based coumarins instead of Iridium-based catalysts to promote the reductive photocleavage of sulfonamides (Scheme 1).

We began our investigation by synthesizing differently substituted pCp-based coumarins. These compounds were rapidly obtained on synthetically useful scales (2 mmol) starting from 4-hydroxy[2.2]paracyclophane[18] and following a procedure previously developed in our laboratory (Scheme 2).[17b] Esterification of pCp **1** with different propiolic acid derivatives and subsequent gold-catalysed cyclization of esters **2a-c** allowed us to isolate products **3a-c**

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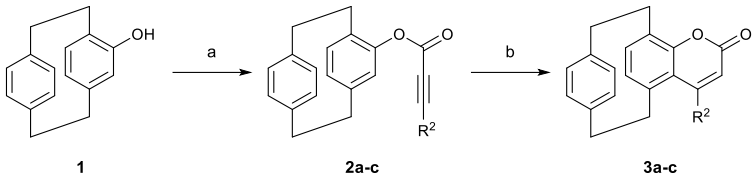
incorporating a methyl, an isopropyl or a phenyl substituent on their heterocyclic moiety. Spectroscopic characterization revealed that these coumarin dyes can absorb light at 300-330 nm in CH_2Cl_2 (Table 1). In this solvent, compounds **3a-c** also display broad emission bands with maxima around 435 nm or 460 nm depending on the nature of their substituents (Table 1).



1 2a-c 3a-c

Reaction contitions: a) propiolic acid (1.5 eq), DCC (1.5 eq), DMAP (0.15 eq), CH_2Cl_2, rt, 4h; b) Echavarren's catalyst (5 mol %), DCE, Ar, 80 °C, MW, 30 min.

Scheme 2. Synthesis and spectroscopic properties of pCp-based coumarins

Table 1. Spectroscopic characterization of pCp-based coumarins

Entry	Product	R^2	λ_{abs} (nm)[a]	λ_{em} (nm)[b]
1	**3a**	Me	304, 324, 370	443
2	**3b**	*i*-Pr	303, 321, 370	441
3	**3c**	Ph	288, 305, 332, 378	465

a) 10^{-5} M solution in CH_2Cl_2; b) 10^{-4} M solution in CH_2Cl_2.

We next set out to study the ability of pCp-based coumarins **3a-c** to promote the photocleavage of N–S bonds in combination with the Hantzsch ester (**7**, Table 2). To this end, an *N*-sulfonylated model compound (**4a**, Table 2) was prepared starting from benzylamine via a tosylation and subsequent benzoylation reaction (see the SI for more information). With this compound in hand, we first tested the photodesulfonylation under light irradiation at 300 nm in the presence of catalyst **3a** (20 mol %) and **7** (1.2 equiv.), using dichloromethane as the solvent. Under these conditions, we were pleased to observe that the reaction reached 66% conversion after 2h (Table 2, entry 1). Note that a longer reaction time (16h) only slightly improved the reaction outcome (Table 2, entry 2). The catalytic charge could be reduced to 5 mol % without any significant loss in the reaction efficiency (Table 2, entries 3 and 4). Performing the transformation under more diluted conditions did not have a remarkable impact on the outcome (Table 2, entry 5). Different solvents were then tested. The reaction failed to occur in both toluene and DMSO (Table 2, entries 6 and 7) due to the poor solubility of the reaction partners in these media. Low conversion was observed when the reaction medium was irradiated at 350 nm for 2h (Table 2, entry 8). Notably, compound **3b**, incorporating an isopropyl group on its coumarin moiety, also prove to catalyse the photodeprotection as 56% conversion could be reached after 2h (Table 2, entry 9). On the contrary, derivative **3c**, displaying an aromatic substituent on its core, delivered product **5a** in a less efficient fashion (Table 2, entry 10). Control reactions were performed and proved the utility of all reaction partners. Light irradiation was found to be essential for the reaction to work, as no product **5a** was formed when the detosylation was performed in the dark (Table 2, entry 11).

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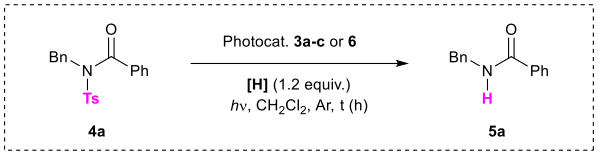
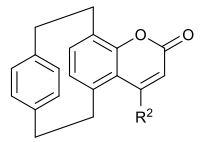
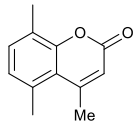
Table 2. Optimization of the photodetosylation reaction





3a-c



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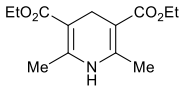

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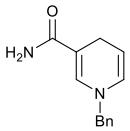

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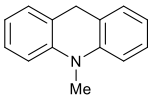

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Entry	Photocat. (mol %)	[H]	t (h)	Conv. (%)[h]
1	**3a** (20)	**7**	2	66
2	**3a** (20)	**7**	16	71
3	**3a** (15)	**7**	2	63
4	**3a** (5)	**7**	2	65
5[a]	**3a** (5)	**7**	2	64
6[b]	**3a** (5)	**7**	2	-
7[c]	**3a** (5)	**7**	2	-
8[d]	**3a** (5)	**7**	2	25
9	**3b** (5)	**7**	2	56
10	**3c** (5)	**7**	2	26
11[e]	**3a** (5)	**7**	2	-
12	**3a** (5)	-	2	-
13	**-**	**7**	2	9
14[f]	**3a** (5)	**7**	2	19
15[g]	**3a** (5)	**7**	2	-
16	**3a** (5)	**8**	2	-
17	**3a** (5)	**9**	2	-
18	**3a** (5)	*n*-Bu_4NBH_4	2	-
19	**6** (5)	**7**	2	14

Reactions were performed in a Rayonet photochemical reactor equipped with eight 300 nm lamps (T = 29 °C, c = 0.05 M). a) Reaction performed under more diluted conditions (c = 0.025 M); b) Reaction performed using toluene as the solvent; c) Reaction performed using DMSO as the solvent; d) Reaction performed by irradiation at 350 nm; e) Reaction performed in dark (T = 25 °C, c = 0.05 M); f) Reaction performed under an oxygen atmosphere; g) Reaction performed in the presence of TEMPO (1 equiv.); h) determined by ^{1}H NMR analysis of the crude reaction mixture.

Compound **4a** did not undergo the photodeprotection in the absence of the Hantzsch ester (Table 2, entry 12), and only traces of product **5a** were observed in the absence of the catalyst

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(Table 2, entry 13). This last result presumably arises from the fact that both the Hantzsch ester and the model compound **4a** can absorb light at 300 nm. Note that the background reaction between the substrate and **7** was previously reported in the literature.[15]

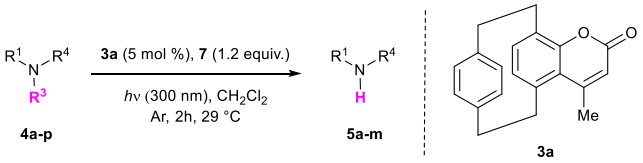
In the absence of the catalyst, however, the photodesulfonylation does not allow to isolate the desired product in a good yield even after irradiating for 16h. The reaction efficiency was significantly decreased when performing the transformation under an oxygen atmosphere (Table 2, entry 14). No conversion was observed when a radical scavenger (TEMPO, 1 equiv., Table 2, entry 15) was added to the reaction mixture, suggesting that the N-S bond cleavage occurs via the formation of radical intermediates. Different hydrogen donors were also screened, including 1,4-dihydronicotinamide **8**, acridine derivative **9** and *n*-Bu_4NBH_4, but all failed to deliver product **5a** (Table 2, entries 16-18). Finally, the paracyclophane-deprived coumarin **6** was tested and proved to be unreactive. Indeed, in this case, a conversion of 14% was observed (Table 2, entry 19), comparable to that obtained in the absence of the catalyst. This last result confirms the necessity to employ a pCp-based compound to promote the transformation. The optimized detosylation of **4a** (Table 2, entry 4) was also performed on the millimolar scale. In this case, product **5a** was isolated in 57% yield by irradiating the reaction mixture for 16h.

We next turned our attention to the reaction scope (Table 3). The cleavage of different sulfonyl groups (Ts, SO_2Ph, SO_2Mes) was tested in the presence of **3a** (5 mol %). Analogously to the Ts group (Table 3, entry 1), a phenyl sulfonyl moiety could easily be removed to afford product **5a** in 59% yield (Table 3, entry 2). Mesityl and mesyl groups, however, could not be removed under the same conditions as only traces of product **5a** were isolated after the reactions (Table 3, entries 3 and 4).

Tosylated precursors bearing various substituents were well-tolerated, including differently substituted (hetero)aromatic motifs, alkyl chains and even a Boc group (Table 3, entries 5-12). Compounds incorporating different aroyl moiety reacted as well (Table 3, entries 13 and 14), even if a modest yield was obtained in the presence of an electron-donating group (Table 3, entry 14). Starting form enantiopure compounds **4o** and **4p**, products **5l** and **5m** were as isolated in 36% and 30% yields respectively without any loss in their enantiopurity, thus demonstrating that base-sensitive stereogenic centers did not racemize under the optimized reaction conditions (Table 3, entries 15 and 16).

Note that the presence of an aroyl moiety on the sulfonylated precursors was required for the reaction to work. Indeed, acetyl, Boc- or Me-substituted sulfonamides **4q-s** proved to be unreactive (Table 3, entries 17-19). Based on this observation, the possibility to perform a chemoselective cleavage of sulfonamides was investigated. Starting from compound **4t**, which incorporates two different tosyl groups, we were happy to observe the formation of the mono-deprotected product **5q** in 61% yield (Scheme 3).

Table 3. Scope of the photodesulphonylation reaction



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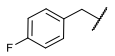
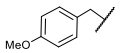
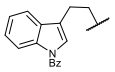
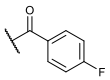
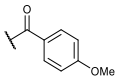
Entry	SM	R^1	R^4	R^3	P[a]	Yield (%)[a]
1	**4a**	Bn	COPh	Ts	**5a**	65
2	**4b**	Bn	COPh	SO_2Ph	**5a**	59
3[b]	**4c**	Bn	COPh	SO_2Mes	**5a**	11
4[b]	**4d**	Bn	COPh	Ms	**5a**	3
5	**4e**		COPh	Ts	**5b**	72
6[b]	**4f**		COPh	Ts	**5c**	60
7[b]	**4g**		COPh	Ts	**5d**	61
8	**4h**		COPh	Ts	**5e**	54
9	**4i**	Me	COPh	Ts	**5f**	58
10	**4j**	*n*-Bu	COPh	Ts	**5g**	56
11	**4k**	Boc	COPh	Ts	**5h**	84
12	**4l**	allyl	COPh	Ts	**5i**	78
13[b]	**4m**	Bn		Ts	**5j**	54
14[b]	**4n**	Bn		Ts	**5k**	39
15[b]	**4o**		COPh	Ts	**5l**	36
16[b]	**4p**		COPh	Ts	**5m**	30
17	**4q**	Bn	Boc	Ts	**5n**	-[c]
18	**4r**	Bn	COMe	Ts	**5o**	-[c]
19	**4s**	Bn	Me	**Ts**	**5p**	-[c]

Reactions were performed in a Rayonet photochemical reactor equipped with eight 300 nm lamps (T = 29 °C, c = 0.05 M). a) Isolated yields. b) The reaction was irradiated overnight. c) The starting material was recovered after the reaction.

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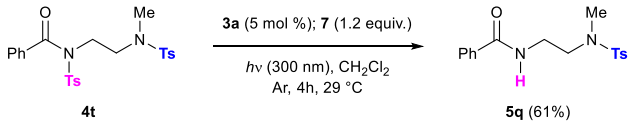

Scheme 3. Chemoselective photocleavage of differently substituted sulfonamides

We finally wished to gain an insight into the mechanism of the photodesulfonylation promoted by the pCp-based coumarins. Theoretical calculations revealed that an energy transfer from the excited states of catalyst **3a** to the lowest excited state of substrate **4a** is endergonic and can therefore be ruled out (see the SI for more details). By analogy with the previously described method relying on the use of an Iridium-based catalyst in combination with the Hantzsch ester,[15] the observed photocleavage of sulfonamides was thus believed to proceed via an electron transfer (ET) pathway. Considering the redox potentials of **3a**, **4a** and **7** as well as the excitation energy (E*) associated with **3a**, the ET process seems to be thermodynamically favourable only when it occurs between the catalyst and the Hantzsch ester (ΔG_{ET} = −0.63 eV, see the SI for more details). On the contrary, direct electron transfer between **3a** and **4a** appears to be unfavourable (ΔG_{ET} = 0.13 eV, see the SI for more details). The formation of electron donor-acceptor (EDA) complexes between the reaction partners was excluded by UV-vis analysis of catalyst **3a** in the presence of increasing quantities of either **4a** or **7**. In addition, we confirmed that the reaction stops as soon as the light irradiation is turned off, therefore excluding the possibility for the photocleavage to happen through a self-sustaining radical process.

Electron paramagnetic resonance (EPR) spectroscopy allowed us to observe the formation of a radical species when the photodesulfonylation was performed in the presence of all the reaction partners. The signal appeared as a single line centered at g = 2.0055 (Figure 1). A similar but significantly less intense signal was observed by monitoring a light-promoted process between the Hantzsch ester **7** and **4a**, thus confirming that a low-yielding background reaction can occur between these two reagents. No EPR signal was recorded in the absence of light, or by mixing only the catalyst and the substrate or the catalyst and the Hantzsch ester.

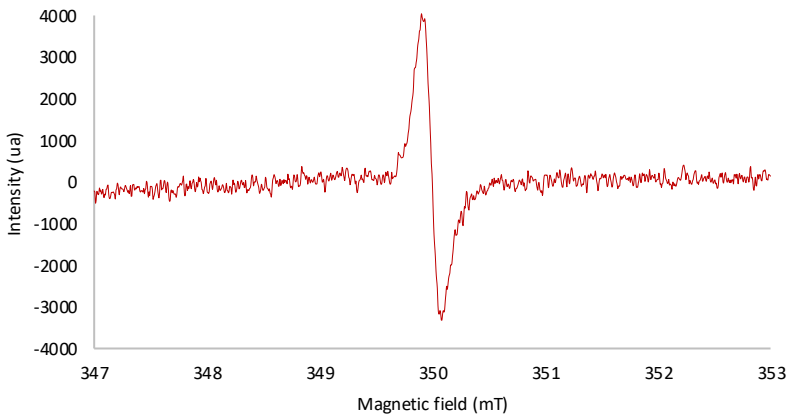

Figure 1. EPR spectroscopy of a solution of **3a** (5 mol %), **4a** (1 equiv.) and **7** (1.2 equiv.) in CH_2Cl_2 (0.05M) under irradiation at 300 nm in a quartz tube under an argon atmosphere.

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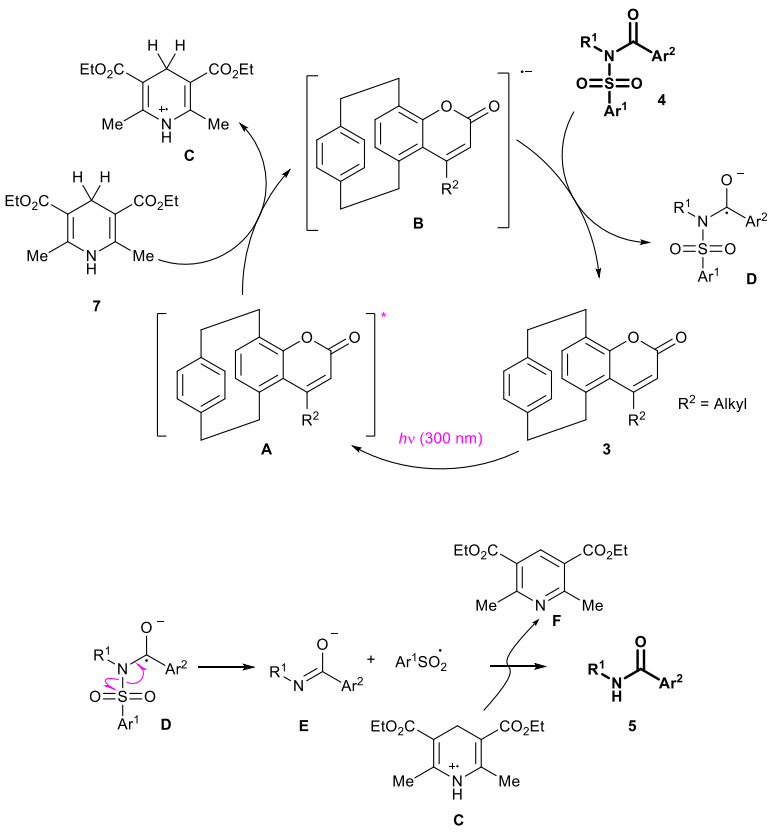
Interestingly, a different radical species was detected while performing a room temperature photolysis of *p*-toluene sulfonyl chloride in the presence of di-*t*-butyl peroxide and triethyl silane. In this case, the observed signal was centered at g = 2.0046, in good agreement with data previously reported for arylsulfonyl radicals ($ArSO_2^{\bullet}$).[19] Note that hyperfine splitting of this EPR signal could be observed, as previously described,[19,20] when generating the radical in toluene at low temperature (193K, see the supporting information for more details). This result allowed us to exclude that $ArSO_2^{\bullet}$ radicals may be the species observed by EPR in our reaction conditions.

Considering all this experimental evidence, the observed transformation is supposed to occur through the mechanism depicted in Scheme 4. The pCp-based catalyst **3** is excited by light irradiation at 300 nm. The resulting excited species (**A**) reacts with the Hantzsch ester **7**. A single electron transfer occurs at this stage, leading to the formation of a dihydropyridine radical cation (**C**) and a coumarin-derived radical anion (**B**). The latter interacts with the reaction substrate **4** to form radical **D** and regenerate the photocatalyst. Note that formation of the reaction intermediate **D** was previously proposed for analogous electrochemical transformations.[12g] This reactive species decomposes through an homolytic cleavage of its N–S bond to afford a carboxamide anion (**E**) and an aryl sulfonyl radical ($Ar^1SO_2^{\bullet}$). Quenching reactions occurring between these species and the dihydropyridine radical **C** finally afford the detosylated product **5**.



Scheme 4. Proposed reaction mechanism.

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DFT calculations were performed to elucidate further this putative mechanism and obtain a better understanding of this novel reaction. First, as previously anticipated, an energy transfer pathway was ruled out as it was found to be thermodynamically unfavoured (ΔG_{EnT} = +1.13 eV, see ESI for details). The free energy of each intermediate was then computed to verify that each proposed step was exergonic (see ESI for details). In an attempt to rationalize the yield discrepancy observed between the photodesulfonylations performed with catalysts **3a**, **6** and **3c** (Table 2, entry 4 vs entry 10 and 18), the difference between the ΔG of the two diverse reactions yielding intermediate **D** (Scheme 4) was calculated. It was found that the photocleavage catalysed by **3c** (compound incorporating a phenyl substituent) has a free energy 5.5 kcal/mol higher than the one promoted by **3a** (compound incorporating a methyl substituent), thus providing a possible explanation for the yield difference. Additionally, TD-DFT calculations were conducted and it was found that the first excited state of **6** is 9.2 kcal/mol higher than that of **3a**, which could explain the yield discrepancy between these catalysts.

Calculations were finally performed to try and clarify the nature of the radical species observed by EPR spectroscopy. Starting from the optimized geometries of the different intermediates, the EPR parameters of all potential radicals were calculated (see ESI for details). The results obtained after this study were in accordance with published g values for the known radical $TsSO_2^{\bullet}$ ($g_{measured}$ = 2.0046; $g_{calculated}$ = 2.0048).[19] Unfortunately, **D** was the only intermediate with a calculated g that would correspond to the observed signal ($g_{measured}$ = 2.0055; $g_{calculated}$ = 2.0050) but its calculated nitrogen isotropic hyperfine coupling (HFC) constant of A_{calc} = 0.14 mT is incompatible with the experimental spectrum obtained by EPR analysis, which does not display any hyperfine structure. The HFCs calculations being known to be quite sensitive to the geometry of the molecules, further studies are ongoing to precisely determine the identity and structure of the radical observed. These will be reported in due course.

Conclusions

In conclusion, we have reported for the first time that [2.2]paracyclophane-fused coumarins can be employed as organophotocatalysts to promote light-induced desulfonyation reactions in combination with the Hantzsch ester. The transformation tolerates various substituents on the starting materials. An aroyl moiety is, however, required on the sulfonylated precursors to observe the formation of the desired products. Experimental mechanistical investigations and theoretical calculations suggest that this reaction occurs via an electron transfer pathway which leads to the formation of a key radical intermediate that requires further characterization. This proof-of-concept study opens new horizons for expanding the range of applications of paracyclophanes in the field of photocatalysis.

Conflicts of interest

There are no conflicts to declare.

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Supplementary Information

Electronic Supplementary Information (ESI) available: [synthetic procedures for the preparation of all products, UV-vis absorption spectra and cyclic voltammograms of the reaction partners, details on the photochemical apparatus, characterization data, theoretical data, copies of ^{1}H NMR and ^{13}C NMR spectra for all the synthesized compounds].

Notes and references

1 C. J. Brown and A. C. Farthing, *Nature* 1949, **164**, 915.

2 H. Hope, J. Bernstein and K. N. Trueblood, *Acta Cryst.* 1972, **B28**, 1733.

3 a) I. Majerz and T. Dziembowska, *J. Phys. Chem. A* 2016, **120**, 8138; b) S. E. Galembeck, R. P. Orenha, R. M. Madeira, L. B. Peixoto and R. L. T. Parreira, *J. Braz. Chem. Soc*. 2021, **32**, 1447; c) D. J. Cram, N. L. Allinger and H. Steinberg, J*. Am. Chem. Soc.* 1954, **76**, 6132; d) D. Klee, N. Weiss and J. Lahann in *Modern Cyclophane Chemistry* (Eds.: R. Gleiter, H. Hopf), Wiley-VCH, Weinheim, 2004.

4 a) J. P. Chen, K. Ueno and K. Suzuki, *Patent No: US 6869698*, 2005; b) H. Goromaru, N. Shigeiwa, M. Murata and S. Maeda, *Patent No: JP 4918803*, 2012; c) G. P. Bartholomew, I. Ledoux, S. Mukamel, G. C. Bazan and J. Zyss, *J. Am. Chem. Soc.* 2002, **124**, 13480; d) J. Zyss, I. Ledoux, S. Volkov, V. Chernyak, S. Mukamel, G. P. Bartholomew and G. C. Bazan, *J. Am. Chem. Soc.* 2000, **122**, 11956.

5 H. Nandivada, H.-Y. Chen, L. Bondarenko and J. Lahann, *Angew. Chem. Int. Ed.* 2006, **45**, 3360.

6 a) D. J. Cram and N. L. Allinger, *J. Am. Chem. Soc.* 1955, **77**, 6289; b) R. S. Cahn, C. K. Ingold and V. Prelog, *Angew. Chem. Int. Ed.* 1966, **5**, 385.

7 a) S. Felder, S. Wu, J. Brom, L. Micouin, and E. Benedetti, *Chirality* 2021, **33**, 506; b) J. Paradies, *Synthesis* 2011, **23**, 3749; c) S. E. Gibson and J. D. Knight, *Org. Biomol. Chem.* 2003, **1**, 1256.

8 a) Y. Morisaki and Y. Chujo, *Bull. Chem. Soc. Jpn.* 2019, **92**, 265; b) Z. Hassan, E. Spuling, D. M. Knoll, J. Lahann and S. Bräse, *Chem. Soc. Rev*. 2018, **47**, 6947; c) S. Felder, M.-L. Delcourt, R. Rodríguez, L. Favereau, J. Jeanne Crassous, L. Micouin and E. Benedetti, *J. Mater. Chem. C* 2023, **11**, 2053.

9 H. Hopf, T. Laue, and M. Zander, *Angew. Chem. Int. Ed.* 1991, **30**, 432.

10 D. M. Knoll, C. Zippel, P. Weis, M. M. Kappes, Z. Hassan, M. Nieger, and S. Bräse, *Dalton Trans.* 2019, **48**, 17704.

11 a) H. R. Snyder and R. E. Heckert, *J. Am. Chem. Soc.* 1952, **74**, 2006; b) D. I. Weisblat, B. J. Magerlein and D. R. Myers, *J. Am. Chem. Soc.* 1953, **75**, 3630; c) E. Wellner, H. Sandin and L. Pääkkönen, *Synthesis* 2003, **2**, 0223; d) B. A. Merrill and E. LeGoff, *J. Org. Chem.* 1990, **55**, 2904; f) N. K. Garg, R. Sarpong, and B. M. Stoltz, *J. Am. Chem. Soc.* 2002, **124**, 13179; g) S. Ji, L. B. Gortler, A. Waring, A. J. Battisti, S. Bank, W. D. Closson, P. A. and Wriede, *J. Am. Chem. Soc.* 1967, **89**, 5311.

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12 a) T. Ankner and G. Hilmersson, *Org. Lett.* 2009, **11**, 503; b) E. Vedejs and S. Lin, *J. Org. Chem.* 1994, **59**, 1602; c) H. Knowles, A. Parsons and R. Pettifer, *Synlett* 1997, **1997**, 271; d) K. L. Jensen, P. T. Franke, L. T. Nielsen, K. Daasbjerg, K. A. Jørgensen, *Angew. Chem., Int. Ed.* 2010, **49**, 129; e) G. Blay, L. Cardona, E. Climent, J. R. Pedro, *Angew. Chem., Int. Ed.* 2008, **47**, 5593; f) M. Kuriyama, T. Soeta, X. Hao, Q. Chen, and K. Tomioka, *J. Am. Chem. Soc.* 2004, **126**, 8128; g) P. Viaud, V. Coeffard, C. Thobie-Gautier, I. Beaudet, N. Galland, J.-P. Quintard, E. Le Grognec, *Org. Lett.* 2012, **14**, 942.

13 I. A. MacKenzie, L. Wang, N. P. R. Onuska, O. F. Williams, K. Begam, A. M. Moran, B. D. Dunietz, and D. A. Nicewicz, *Nature* 2020, **580**, 76.

14 a) E. Hasegawa, T. Tanaka, N. Izumiya, T. Kiuchi, Y. Ooe, H. Iwamoto, S. Takizawa and S. Murata, *J. Org. Chem.* 2020, **85**, 6, 4344; b) J. Brom, A. Maruani, L. Micouin and E. Benedetti, *J. Org. Chem.* 2023, DOI: 10.1021/acs.joc.3c00296.

15 J. X., B.-J. Li, Z.-J. Feng, G.-D. Sun, H.-H. Ma, Z.-W. Yuan, J.-R. Chen, L.-Q. Lu and W.-J. Xiao, *Chem. Asian J.* 2013, **8**, 1090.

16 a) A. Gualandi, G. Rodeghiero, E. Della Rocca, F. Bertoni, M. Marchini, R. Perciaccante, T. P. Jansen, P. Ceroni and P. G. Cozzi *Chem. Commun.* 2018, **54**, 10044; b) A. Gualandi, A. Nenov, M. Marchini, G. Rodeghiero, I. Conti, E. Paltanin, M. Balletti, P. Ceroni, M. Garavelli and P. G. Cozzi, *ChemCatChem* 2021, **13**, 981.

17 a) E. Benedetti, M.-L. Delcourt, B. Gatin-Fraudet, S. Turcaud and L. Micouin, *RSC Adv*. 2017, **7**, 5047; b) M.-L. Delcourt, C. Reynaud, S. Turcaud, L. Favereau, J. Crassous, L. Micouin and E. Benedetti, *J. Org. Chem*. 2019, **84**, 888; c) S. Felder, M.-L. Delcourt, M. H. E. Bousquet, D. Jacquemin, R. Rodríguez, L. Favereau, J. Crassous, L. Micouin and E. Benedetti, *J. Org. Chem.* 2022, **87**, 147.

18 C. J. Friedmann, S. Ay, and S. Bräse, *J. Org. Chem.* 2010, **75**, 4612.

19 a) M. Griesser, J.-P. R. Chauvin and D. A. Pratt *Chem. Sci.* 2018, **9**, 7218; b) J. E. Bennett, G. Brunton, B. C. Gilbert and P. E. Whittall, *J. Chem. Soc., Perkin Trans. 2*, 1988, **1988**, 1359; c) A. G. Davies, B. P. Roberts, and B. R. Sanderson, *J. Chem. Soc., Perkin Trans. 2*, 1973, **1973**, 626.

20 M. C. R. Symons, *J. Am. Chem. Soc.* 1969, **91**, 5924.

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